

Cost comparison of different technologies for Industrial CCS

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Overview

Overview of talk

Introduction

Discussion of methodology

CCS on Power – LCOE

CCS on Industry – Cost of CO₂ avoided

Limitations of the study

Suggestions for necessary research

CCS proposed as **one part** of the solution

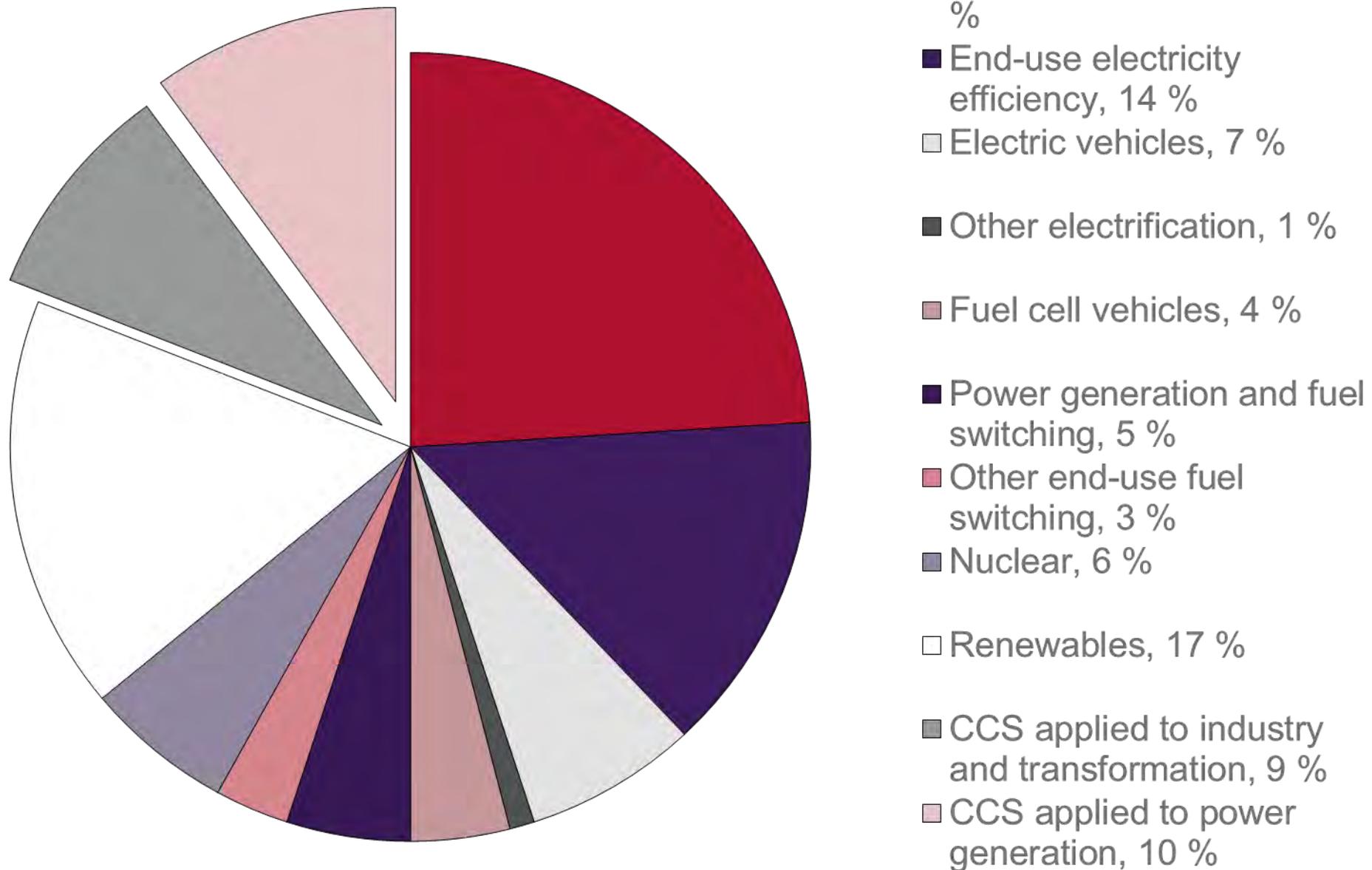


Figure. Total low-cost GHG reduction in 2050 (43 Gt) according to the IEA Energy Technology Perspectives

Definitions... It depends on who you ask

What is a 1st Generation Technology?
APGTF – Short term: 0 – 10 years away

MEA or Oxyfuel – IGCC?
CCS from concentrated
industrial sources

What is a 2nd Generation Technology?
APGTF – Medium Term: 7 – 15 years

Improved solvents, Ca looping?

What is a 3rd Generation Technology?
APGTF – Long term: 10 – 20 years away

MOF, Chemical Looping, NOHMs

Methodology

Systematic Review

Define search term

Refine search terms until a certain number of papers are included in the search (around 500)

Read all abstracts and summarise potential relevance via a questionnaire
– Rank as High/Medium/Low

Full papers for all High relevance studies read

Further key references (e.g. original papers where results are quoted in the paper read) are included

Economic data is extracted, converted to USD at the prevailing exchange rate and a capital cost escalator used to bring all data to a common cost year (here 2013).

Systematic Review

Advantages:

Removes Bias

A wide range of papers are included

Does not require an intimate knowledge of the field

Disadvantages:

A lot of work compared to traditional literature reviews

May miss key, well known references (but see “removes bias”)

Can miss non academic references

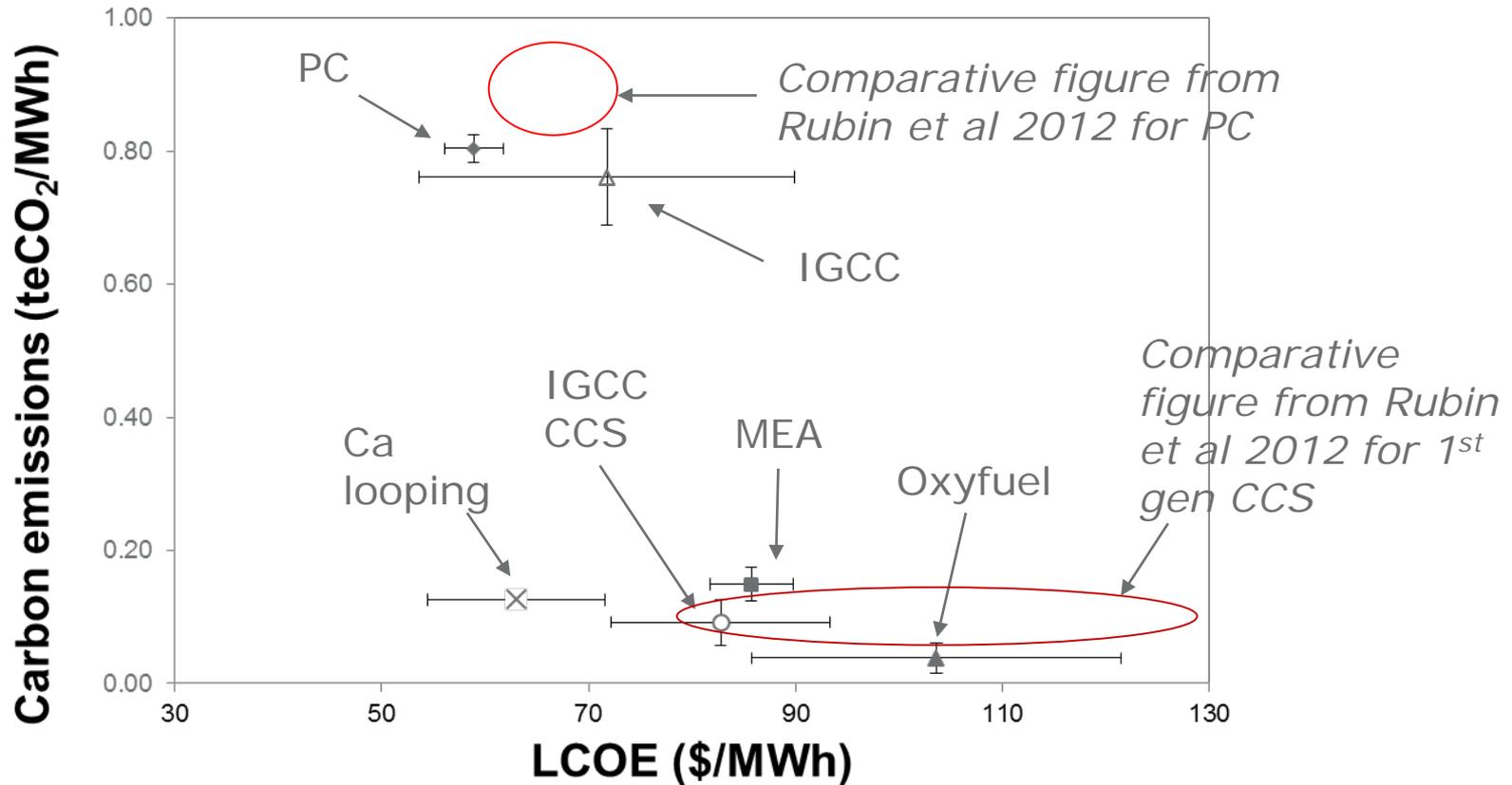
For the work presented here, over 1000 abstracts were read and categorised.

Systematic Review – Electricity Generation

Technology	Number of high relevance papers reviewed		Strength of Evidence		
	Academic Database Searches	Reviewer additions	Technical	Economic	Policy
Amine	33	6	Strong	Strong	N/A
Oxy fuel	24	4	Strong	Strong	N/A
IGCC CCS	21	3	Strong	Strong	N/A
Calcium looping	13	2	Medium	Medium	N/A
Chemical looping	8	2	Medium	Weak	N/A
Policy	32	3	N/A	N/A	Strong

Search terms refined until 619 abstracts located. All abstracts read and categorised – 196 high relevance papers located, with 89 categorised as “highest” relevance (full paper read).

LCOE for a number of Technologies



Not including compression and transport costs

MEA error bars reflect better agreement – more industrial experience

Potentially, lower costs represent less fully developed knowledge

Major Findings

Costs were only included where a full CCS plant model was developed, integrated with a power plant.

Unsurprisingly, the largest number of studies investigated oxyfuel or amine scrubbing.

In general, oxyfuel had a LCOE slightly higher than MEA scrubbing, though the results had greater variability.

IGCC had huge variation in costs calculated – even when CCS was not applied.

Ca looping was the most studied of the 2nd / 3rd generation technologies, and generally had the lowest prices. However, many studies referred one or two initial studies for dual CFB costs; lack of independence in the field.

Owing to the huge variations in baseline cases, it was not possible to reliably convert the costs to a cost of CO₂ avoided.

Large effect of discount rate / financial assumptions noted.

Industrial CCS

Comparison of Industrial Sectors

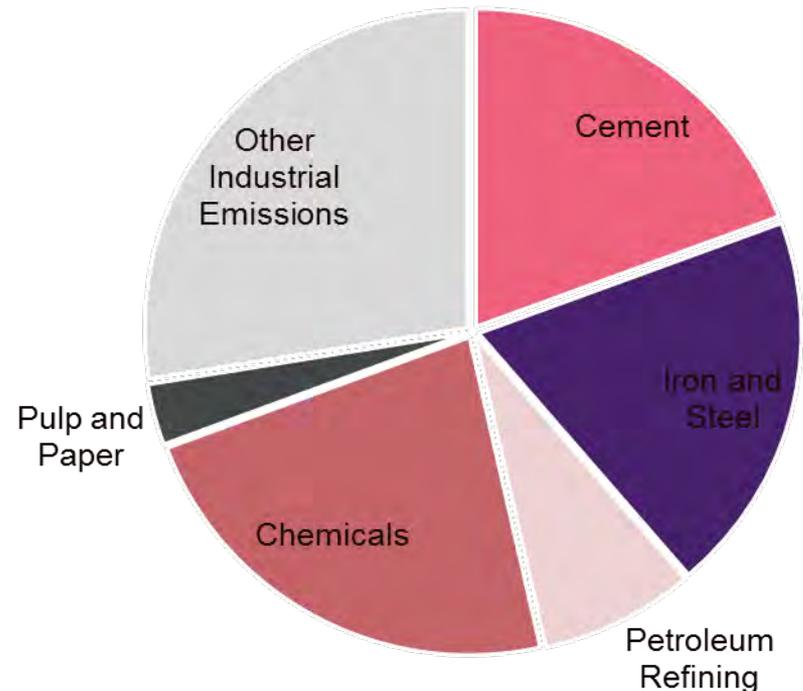
The four largest CO₂ emitting industrial sectors make up almost 75% of industrial emissions.

The sectors discussed in terms of industrial processes are iron and steel production, petroleum refining, chemical manufacturing, cement manufacture and pulp and paper production.

Not including gas processing.

- Chemical manufacture and petroleum refining were amalgamated in this study due to the similar nature of the boilers which CO₂ would be captured from.
- The pulp and paper industry was also investigated due to the large potential for carbon capture in this sector

Global Direct Industrial Emissions
(Mt per annum)



Systematic Review Process - Industrial

Search

- Initial search terms were drawn together to cover the major technological areas of CCS, policy and costs
- Search terms were entered into three academic databases
- Results were recorded, and search terms customised to return a selection of relevant papers; in this case, 525.

Summarise

- All abstracts were screened and non-relevant papers were discarded according to agreed criteria
- All 262 papers deemed relevant in the initial screening were read, summarized and prioritised
- A questionnaire was formulated to allow all relevant data from the papers to be classified

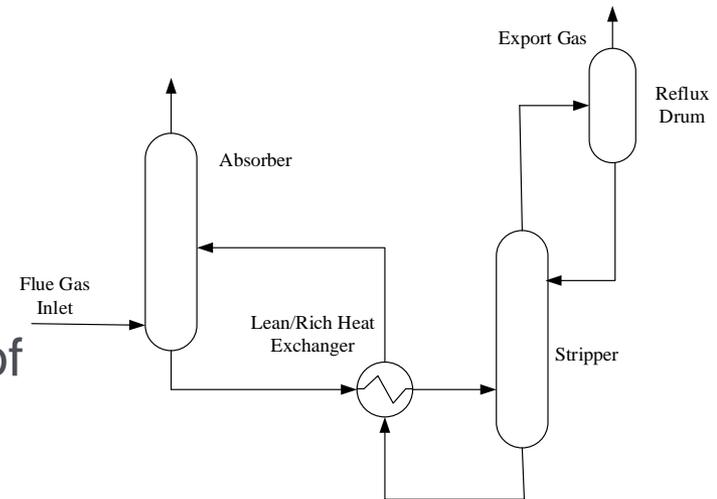
Analysis

- Papers were sorted by industry and information regarding technology, policy or cost noted in questionnaire and compared where applicable
- In order to directly compare capital costs and produce meaningful cost analysis, a cost escalator model was constructed to **convert all costs to 2013 US Dollars**

Main Technological Options for Industrial Carbon Capture

Post Combustion Capture through Amine Solvents

- Amine-based solvents such as MEA and MDEA can strip CO₂ from flue gases with capture efficiencies of >99%,
- This gives a waste gas stream of very high purity CO₂
- Can be easily retrofitted onto existing plants
- Generally high cost of regenerating the solvents, which are often toxic and corrosive



Main Technological Options for Industrial Carbon Capture

Chemical/Metal Looping Technologies

- Operate by repeated reaction and regeneration of a metal oxide or CaO.
- High temperatures are needed to regenerate the solid sorbent.
- Problems with solid transport and **attrition**, and loss of activity of sorbent over time
- Particular synergy where heat or steam is being produced using natural gas as a fuel, or (Ca-looping) in cement manufacture

Main Technological Options for Industrial Carbon Capture

Oxyfuel Combustion

- By burning fuels in pure oxygen (plus recycled CO₂) instead of air, the flue gas is almost pure CO₂.
- Can provide heat for boilers and furnaces, e.g. in iron and steel mills
- Using a smaller volume of oxygen than air means that process equipment can be smaller, so lower capital costs (oxyfuel in cement plant)
- Requires large, energy intensive air separation unit

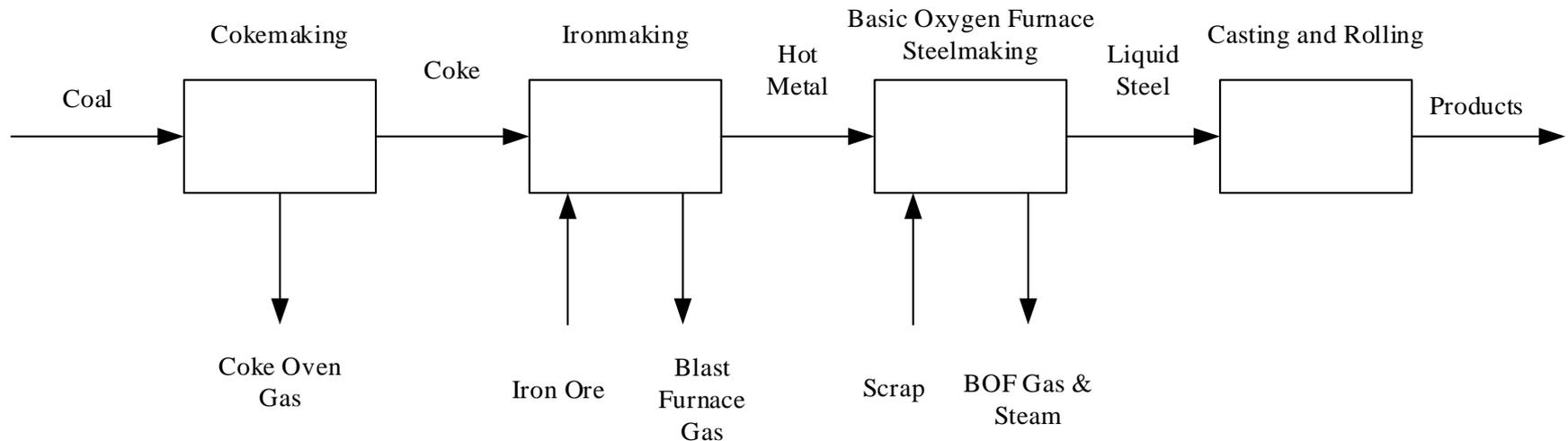
Main Technological Options for Industrial Carbon Capture

Other technologies

- » Mineral carbonation of waste slags forms stable carbonates on reaction with CO_2 , although a limited capture potential and low TRL
- » Biological systems using bacteria or algae to capture CO_2 are still in early development
- » Membranes to directly separate CO_2 from flue gases have been trialled, but little cost data for large scale use exists
- » Formation of hydrate compounds on reaction with CO_2 which can be filtered out of flue streams

Carbon Capture on Iron & Steel Production Facilities

- Large point-sources of CO₂ mean that the iron and steel industries are comparatively well suited to having carbon capture implemented on them.
- Waste process heat can be used in regeneration of the amine sorbent, reducing the energy cost associated with post combustion capture technologies through heat integration



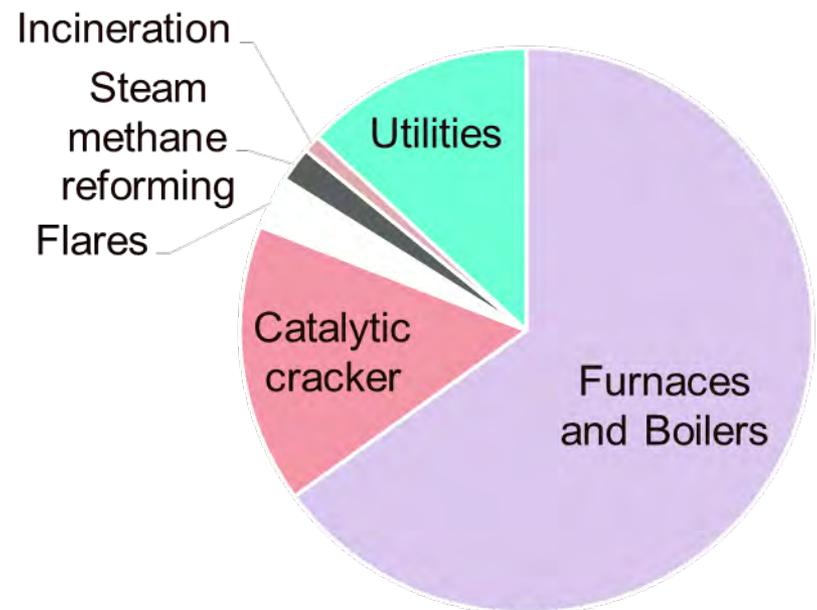
Carbon Capture on Iron & Steel Production Facilities

- Vast majority of research regards using amine sorbents for post combustion capture
- Post combustion using MEA found to cost between \$59-116/tCO₂ on different plant items, such as the coke oven and blast furnace
- Using a shift reactor and a Selexol amine solvent, carbon capture reported to cost 24-27\$ per tonne captured.
- Potential for use of steel waste slags for mineral carbonation, though large variations in reported costs and very low capture potential

Carbon Capture on Petroleum Refineries and Chemical Manufacturing

- 60% of emissions from the industry come from various furnaces and boilers, with utilities making up about half of the remainder
- This means that CCS will struggle to reduce emissions greatly unless applied to multiple point sources at a vastly increased cost
- Nature of refineries as long serving process plants means that retrofit potential (as with amine scrubbing) is an important factor for plant owners

Emissions Sources and Percentages

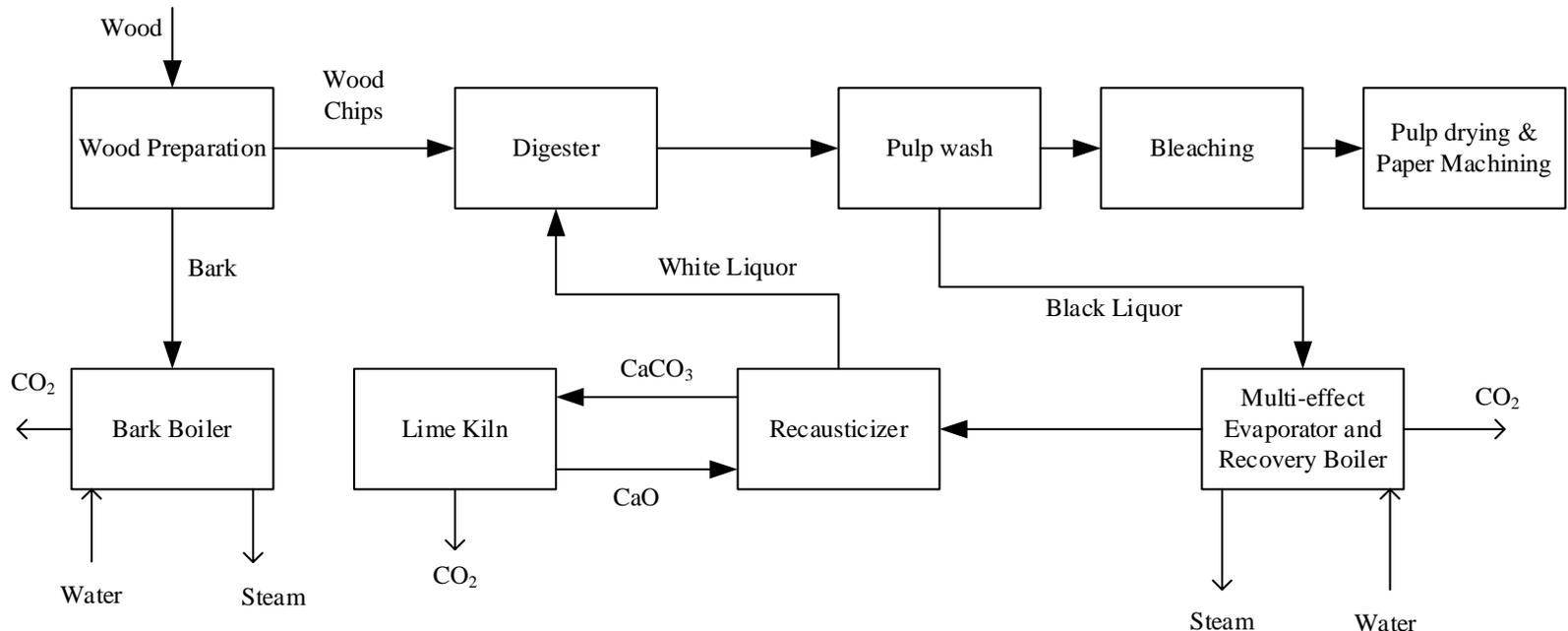


Carbon Capture on Petroleum and Chemical Refineries

- Post combustion amine capture ranges in cost from \$69 -123 depending on capture location and method, with the preferred location a combined stack able to mitigate about 50% of emissions
- When applied to a gasifier, post combustion capture can be effected for the lower cost of \$41 per tonne, but with a capture potential limited to 15% of plant emissions.
- Oxyfuel combustion can capture a higher proportion of the CO₂ at a cost of \$65/tCO₂ which can be used to mitigate emissions from various plant items at the same time
- Chemical looping can be applied to the refinery boilers at costs of \$44-58 per tonne depending on the solid replacement rate active in the system

Carbon Capture on Pulp & Paper Production Facilities

- Research into retrofitting post-combustion CCS onto large boilers.
- New plants will utilise black-liquor gasification technologies to reduce emissions and can be combined with post-combustion capture
- Pulp and paper mills are often located away from other industries in sparsely populated countries, such as Sweden or Finland

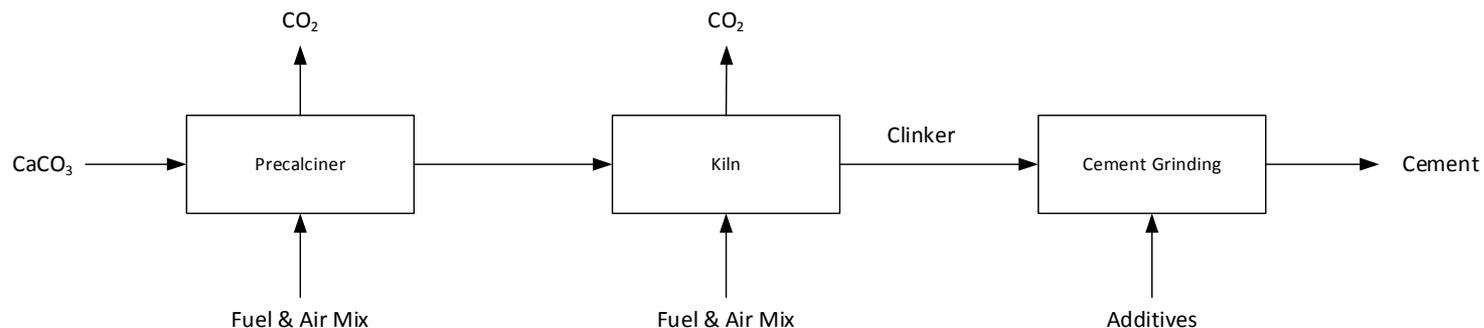


Carbon Capture on Pulp & Paper Production Facilities

- Small volume of research available, with both papers that discuss costs considering post-combustion capture of boilers
- Boiler flue gas captured at cost of \$15 per tonne on a standard plant for 62% of CO₂ captured
- Black liquor gasification process used followed by amine capture gives a higher cost of \$34 but with a capture potential of over 90%.
- Potential for significantly higher transport costs due to isolated location not considered here but may make process economics significantly less favourable

Carbon Capture on Cement Plants

- 5% of all global CO₂ emissions can be attributed to the cement manufacture process.
- Within the process, 60% of the emissions are due to the calcination reaction and the other 40% attributable to combustion for heat generation
- Hence pre-combustion can only capture a maximum of 60% of emissions, though with energy costs this is reduced to around 52%
- Impurities in the flue stream such as SO₂ and dust can cause amine scrubbing units to have high heat duties and necessitate a high degree of solvent regeneration due to side reactions

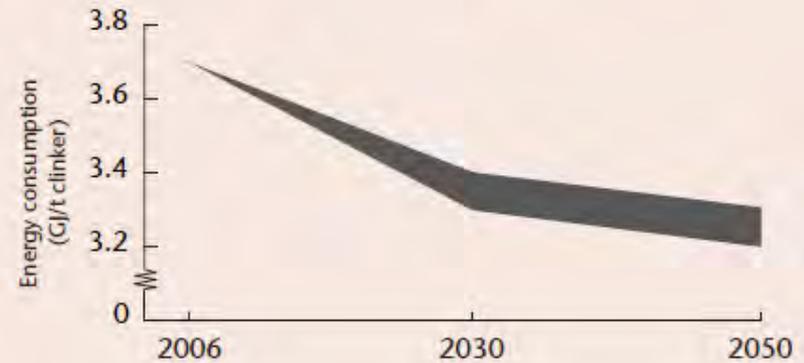


Potential mitigation options

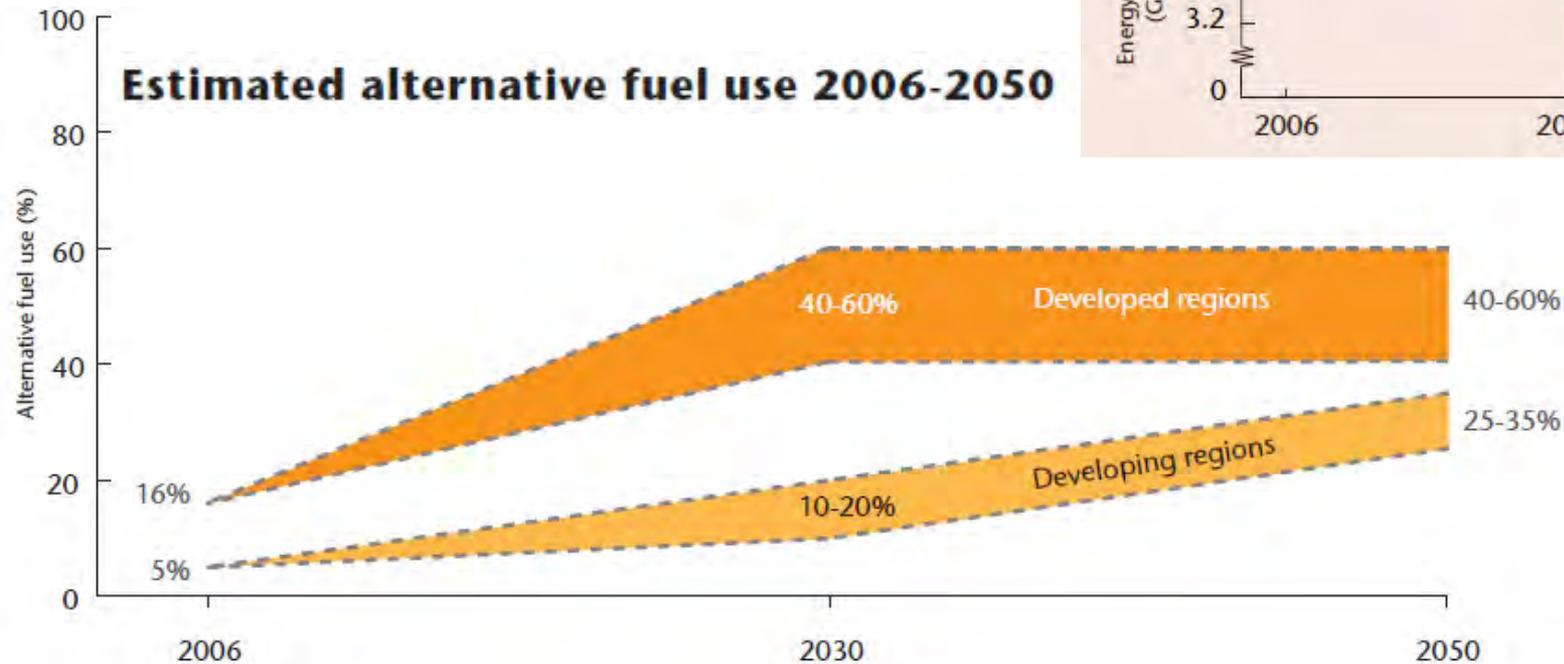
Clinker content:
78% (2006) → 71% (2050)

Thermal efficiency

Thermal energy consumption for clinker manufacture in different years:



Estimated alternative fuel use 2006-2050



Source:
WBCSD/IEA
Cement
Roadmap, 2011

Carbon Capture on Cement Plants

- Two major technologies costed for cement plants – amine post-combustion capture and calcium looping
- Research near-evenly split between the two technologies
- Post combustion capture has an estimated capture cost of \$106 per tonne for cement plants (costs can be significantly lower if only partial CO₂ capture is used – about 40 % of the CO₂ onsite can be captured without building a CHP plant as a source of low-grade heat).
- Calcium looping technologies average at \$38 per tonne, though are less developed
- Oxy-combustion has been investigated and estimated at an average cost of \$55 per tonne.

Kiln Substitution – Fluidised-bed Advanced Cement Kiln System (FAKS)

- *Fluidised beds increase heat & mass transfer efficiency within kiln*
- *Combustion process requires a lower temperature*
- *Less coal needed to burn for fuel*

Availability of Technology: *Large pilot plants (200 tpd and 1000 tpd) have been developed in 1996 and 2005 respectively.*

Key Advantages³

- ✓ *Lower capital and maintenance costs (compared to traditional rotary kiln)*
- ✓ *Improve heat recovery efficiency by 20%*
- ✓ *Reduction in NOx emissions*
- ✓ *Wider variety of fuels can be used*

Associated Risks

- *Fluidised-bed kilns have limited capacity*
- *Investment costs uncertain*

Not enough analysis of costs as yet

1 Hashimoto, I., Watanabe, T. (1999) *Clinker Burning in The Fluidized Bed - An Innovative Technology.*

2 European Cement Research Academy (2009) *Technology Paper No 14: Fluidized Bed Advanced Cement Kiln System.*

3 "Energy Efficiency and Resource Saving Technologies in Cement Industry" APP Cement Task Force, Asia-Pacific Partnership, Page 77

Cost Comparisons for Industrial Processes

	Iron and Steel		Refineries		Pulp and Paper		Cement	
	Cost (USD 2013)	Number						
Post-combustion	74.23	5	77.60	5	24.73	2	106.53	3
Oxy-combustion	N/A	0	65	1	N/A	0	59.46	1
Mineralisation	62.50	2	N/A	0	N/A	0	N/A	0
Calcium Looping	N/A	0	51	1	N/A	0	37.78	4

Figures from
UNIDO 2011
(rebased)

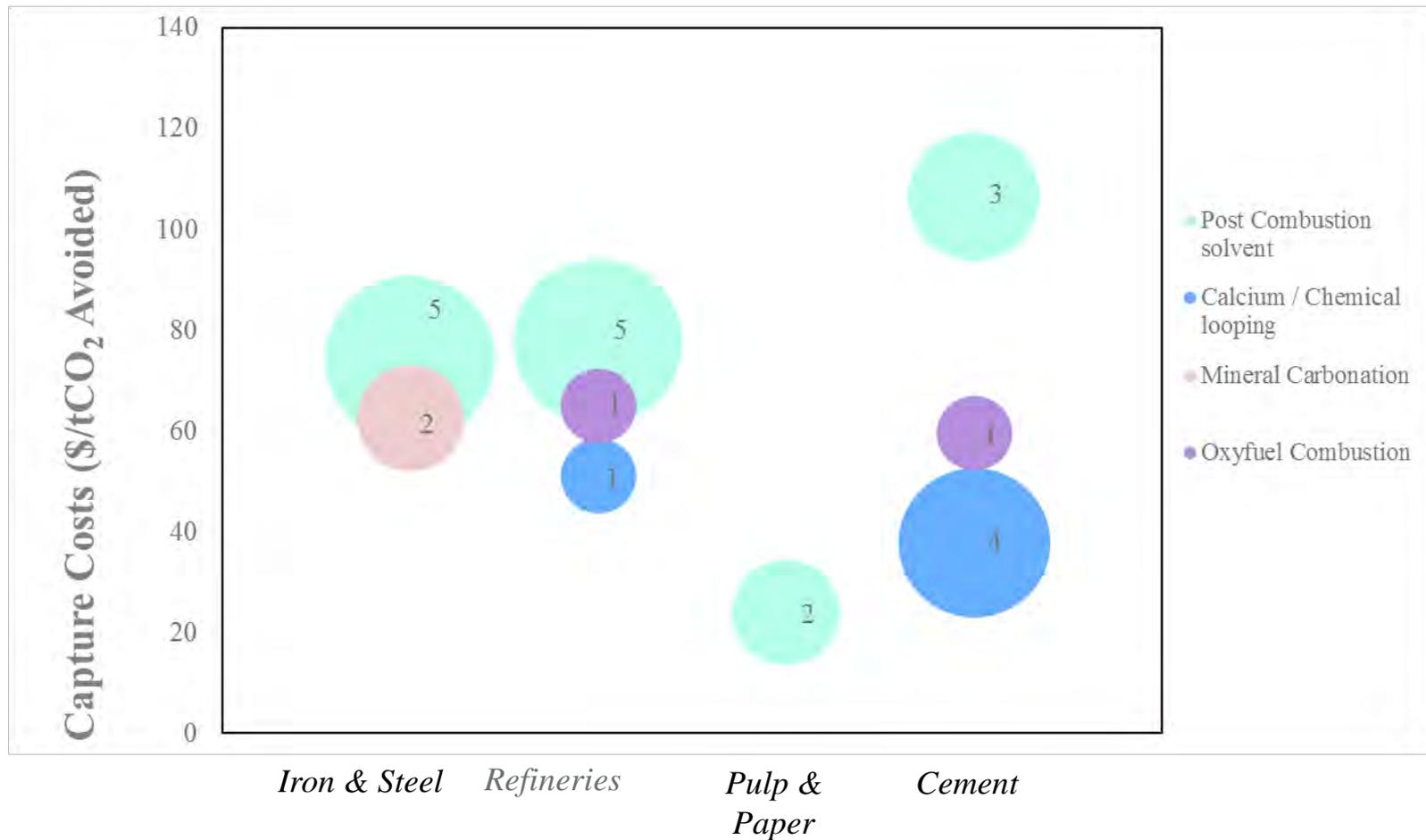
Low	High
64.8	86.4

Low	High
48.6	129.6

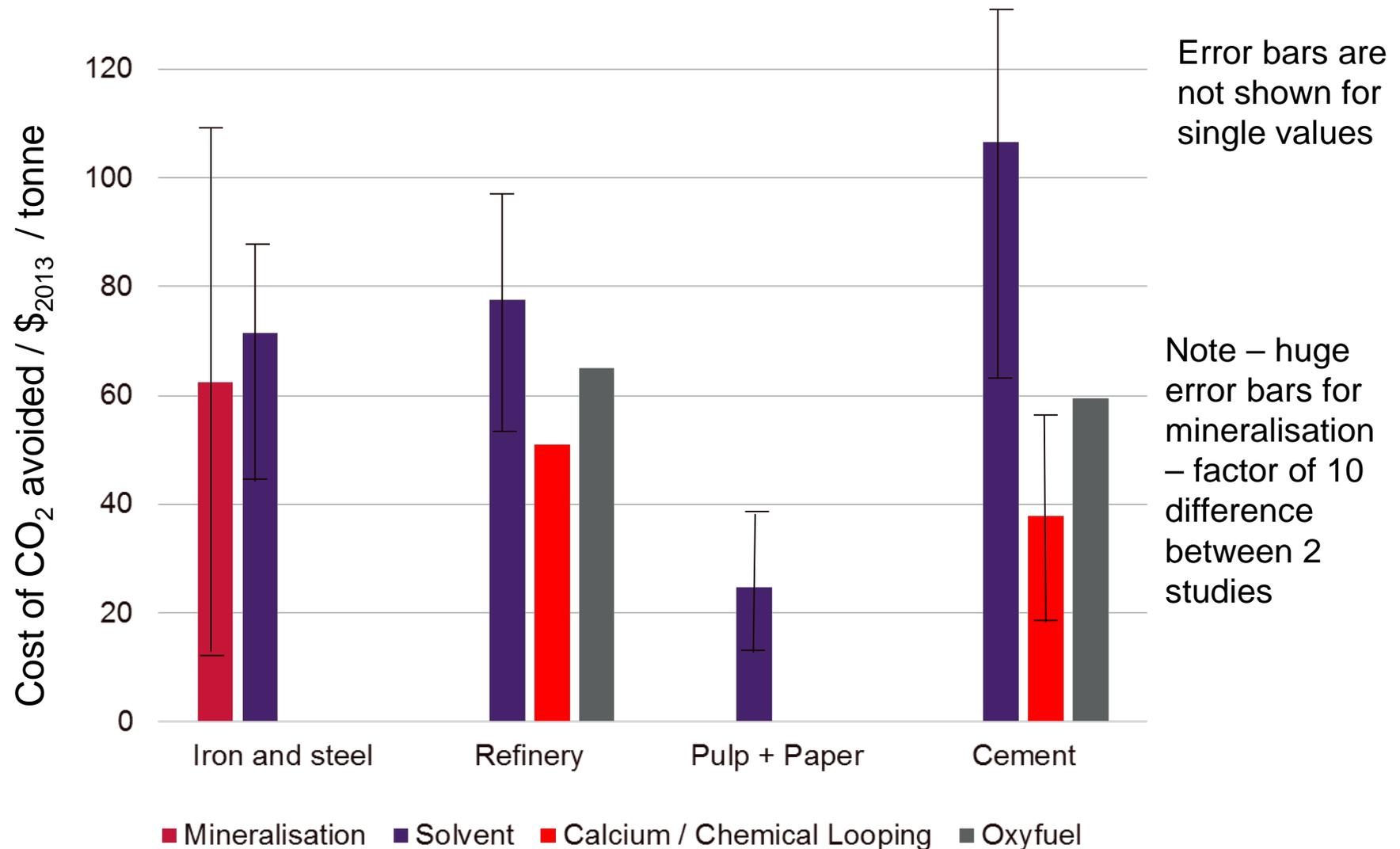
Low	High
59.4	162

Unido includes transport and storage, and a wide range of future techs (Hlsarna / Finex for iron making, etc).

Relative Abundance of Cost Information for Industrial Carbon Capture



Cost Information for Industrial Carbon Capture (including Standard Deviation)



Major Findings

Costs were only included where a full CCS plant model was developed, integrated with the industrial process of interest.

Post combustion solvent scrubbing was most prominent, but a large number of studies of cement with Ca looping

Solvent scrubbing frequently the most expensive option investigated – for cement, this is because there is insufficient low-grade heat available onsite – a CHP plant is necessary (though partial capture up to 50 % may be a cheaper, more viable option).

Where the aim is purely to produce heat, and gas is currently burned, chemical looping is an excellent choice. (unless pressurised, CLC with natural gas is a non-starter on the grounds of efficiency, for power generation).

But – don't forget that post-combustion capture using solvents has the big advantage of not having any potential adverse effects on the clinker.

Comparison / Power and Industrial CCS

- Cost of Capital was one of the major determinants, for both power and industrial CCS, of profitability.
- Post combustion amine capture is comparatively cheaper for power production than when applied to industrial CCS (excepting pulp and paper – though limited number of studies).
- Calcium looping is low in cost for both sectors, with particular applicability to cement CCS.

Non systematic – comparison between Ca looping and Chemical Looping

Chemical Looping

Cost / 2013 USD

(low high)

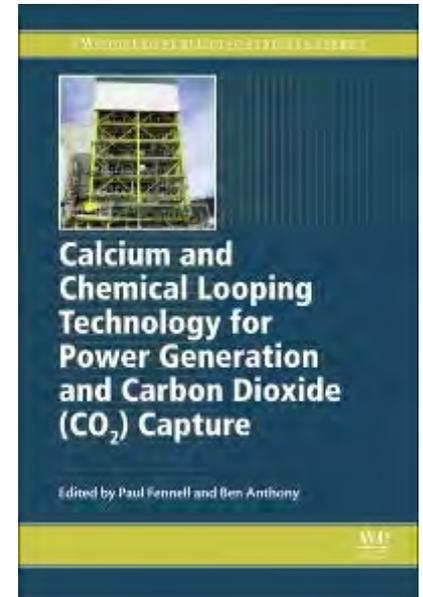
Authors	(low)	(high)	
Melein and Roijen (2009)		43.86	Refinery boiler (low replacement)
Melein and Roijen (2009)		56.97	Refinery boiler (high replacement)
Lyngfelt and Linderholm (2013)	15.42	33.74	Power station (extreme range)
Lyngfelt and Linderholm (2013)	24.10	25.06	Power station (likely range)
Morin et al (2006)	12.53	17.35	Power station
ZEP (2011)		24.77	Rebasing of Morin et al according to ZEP guidelines

Calcium Looping

Cost / 2013 USD

(low high)

Authors	(low)	(high)	
MacKenzie et al (2007)		30.43	Pressurised CFB
Cormos (2014)		33.10	Gasifier gas, precombustion
Cormos (2014)		36.80	Gasifier gas, post-combustion
Abanades et al (2007)		15.20	Power station
Romeo et al (2009)		17.76	Power station
Romeo et al (2011)		16.62	Power station + cement works
Rodriguez et al (2012)		21.93	Cement works

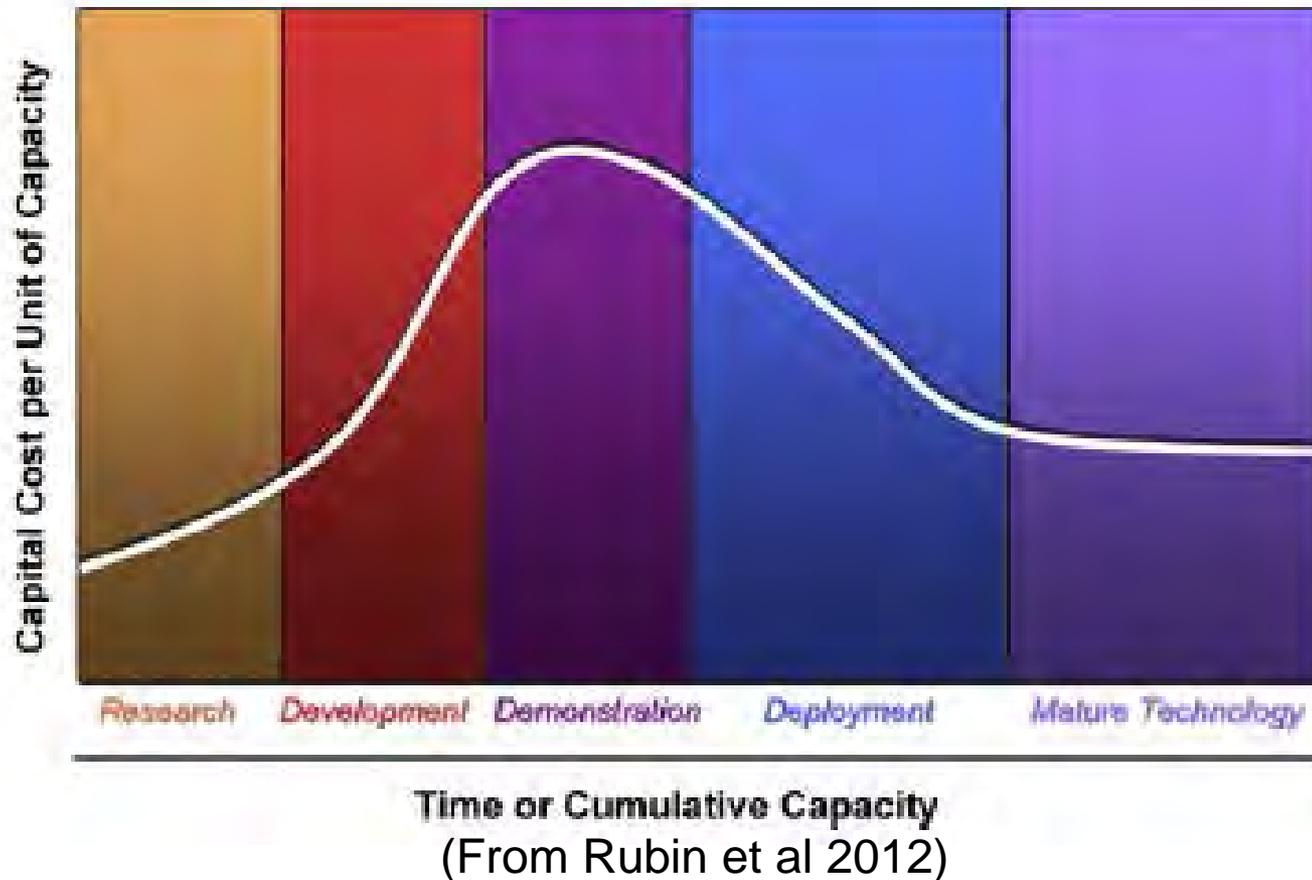


Shameless plug for new book

Issues with the studies / Future work needed

- A number of technologies are missing from the analysis, which now requires broadening to include them. In particular, low temperature solid sorbents need specifically investigating.
- CCS for natural gas sweetening has not been included.
- The methodology employed does not allow for significant improvements in technologies with time – though in many cases there are insufficient studies to allow comparison.
- One major finding is that there are simply not enough independent studies of different CCS technologies applied to industry, and not enough techno-economic studies of new sorbents in realistic process models.
- **All work – must give both the unindexed costs, CAPEX / OPEX, etc and assumptions, etc plus any financial models. Too much variability in financial assumptions for cross-technology comparison, even before differences of baseline technological assumptions.**

Technological development pathway



Rubin is pessimistic, and thinks that many novel processes will never get over the hump – they will be beaten by more mature technologies, even if sub-optimal. Personally, I think it all depends on a decent forward carbon price.

Final word on Economics

Oil prices rise 6% as Saudi Arabia bombs Yemen rebels

🕒 2 hours ago | **Business**

Eventual
energy
precu

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REUTERS

The airstrikes came after Iran-backed rebel groups marched on the port city of Aden

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UKCCSRC Phase 2 – UK Demonstration of Enhanced Calcium Looping and First Global Demonstration of Advanced Doping Techniques

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EPSRC

Engineering and Physical Sciences
Research Council



Further References

Rubin, E. S., Mantripragada, H., Marks, A., Versteeg, P. & Kitchin, J. "The outlook for improved carbon capture technology" Progress in Energy and Combustion Science 38, (2012); 630-671.

<http://www.amazon.com/Chemical-Technology-Generation-Woodhead-Publishing/dp/085709243X>